Summary of PEEK Tube Studies

Heat transfer measurements and calculations

Tubing formed to 5.4mm x 2.0mm outside dimensions was assembled into a core structure with CF skins. Heaters were placed on the skins at the SVX chip locations and several RTDs were used to measure the CF skin temperature at various locations. An ANSYS model of this mock-up was built and the results compared with the FEA model. The mock-up was kept simple so that we could measure the heat transfer coefficient of the fluid with minimal error due to heat transfer through material layers (e.g. dummy silicon, glue joints etc). The measured heat transfer coefficient was about 650 W/m^2K. These results are documented in a note by G. Lanfranco dated 10-April-2002 [1]. This work also verified the accuracy of the pressure drop versus flow calculations being used[2].

Subsequently a full mechanical prototype stave was tested to verify the cooling system design. Tubing formed to 7.0mm x 1.9mm outside dimensions was assembled into a core structure built per drawing 399746 Stave Core Assembly. The stave was assembled with blank silicon modules, outfitted with blank BeO hybrids. Electrical heaters were attached to the blank hybrids to simulate the heat load of the SVX chips. Several RTDs were used to measure the silicon and hybrid temperatures at various locations. An ANSYS model of this prototype was built and the test results compared with the FEA model. These results are documented in a note by G. Lanfranco and D. Olis dated September 2, 2003.[3] The test shows the design of the cooling tube and the operating parameters of the coolant will manage silicon temperatures in Layers 2-5 as required. Silicon temperatures will not exceed 0º C. Additionally, the finite element model is validated.

Finally, an FEA was run[4] with a tube geometry of 6.88mm x 2.0mm (OD), very close to the shape we are producing now (7.0mm x 1.9mm) and with a 0.225mm epoxy/Kapton layer between the tube wall and the sensors. A heat transfer coefficient of 695 W/m2K was used, based on scaling the measured value to the new geometry. The maximum silicon temperature in the FEA was –1.9º C with a bulk coolant temperature of –14º C, meeting the design specification of <0º C with –15º C coolant at the inlet. The testing shows this result is conservative. Note that Frank Lehner has calculated[5] the expected depletion voltage in L2 operating at +10º C to be ~150V with a signal to noise ratio >10:1 for T=+5º C at 15fb-1. This implies that the staves would continue to function

[1] \\Ppdserver\MD.PPD\Projects\SiDet\Engineering_Notes\PEEK_Testing\Heat transfer study on D0 Run2b stave.pdf
[2] \\Ppdserver\MD.PPD\Projects\SiDet\Engineering_Notes\PEEK_Testing\Pressure Drop in D0 Run2b Stave.pdf
[3] \\Ppdserver\MD.PPD\Projects\SiDet\Engineering_Notes~~\PEEK_Testing\Heat transfer study on D0 Run2b stave.pdf~~ **\Stave cooling model&test-Enote**.pdf
[4] \\Ppdserver\MD.PPD\Projects\SiDet\Engineering_Notes\PEEK_Testing\FEA - staves analysis.pdf
[5] D0NOTE 3959, draft 5.0, http://d0server1.fnal.gov/projects/run2b/silicon/www/smt2b/Sensors/sensors.html

without noticeable degradation even if the coolant system were only capable of delivering –10º C coolant.

Adhesion tests

Two types of adhesion tests have been done. The first set used blocks of PEEK material to measure the shear strength of PEEK to PEEK joints with 0.003" glue lines. Renee Duncan[6] and Ben Nitti[7] both performed these measurements, with different adhesives. The main thrust was to evaluate adhesion of PEEK nuts to hybrids. Measurements ranged from 415-815psi using 3M 2216 adhesive and 213-645psi using Ablebond 84-3 adhesive, a product one of the hybrid stuffing vendors uses regularly for mounting components. Note that the lower values represent adhesive failures due to poor surface preparation while well prepared surfaces show cohesive failure with shear strengths >400psi generally.

A second test was done to look directly at the adhesion between the skin and cooling tube of a stave core during vacuum leak check. We used a poorly constructed core that had many voids in the glue line between the tube and skin. These provide points of stress concentration from which we would expect to see failure propagate. The PEEK tube was evacuated and let up to atmosphere repeatedly (6-7 times). The core was then continually pumped on for 24 hours. As an extreme test LN2 was poured on one surface while the tube was evacuated. The core curled up 3-4" off the table due to the temperature differential. No sign of glue failure was observed. This test verifies that we can use internal vacuum to do leak testing once the stave cores are assembled. The test also demonstrates that peel between the PEEK tube and Kapton skins is not a concern. Leak testing of free-standing tubes is discussed below.

Ne leak check

A Ne leak check apparatus was developed at PAB for Mylar straw tubes. We are using it to test formed PEEK tube assemblies built per drawing 399712. The tube assembly is placed inside a vacuum chamber and a Dupont leak detector tuned to Ne samples the vacuum outside the tube. The tube is then evacuated and back-filled with Ne to a pressure slightly above atmospheric. We tested all but one[8] of the first 6 tubes produced in the new 7mm x 1.9mm mold. These tubes were leak tested alone, not as assembled. The peak leak rates were 1.5-6.4 x 10-5 STD-CC/sec. It was observed that after 5-10 minutes the leak rates began to fall again. This phenomenon is not yet understood, but may be due to changes in permeability with moisture content of the PEEK. In production, the full tube assembly will be leak-tested to verify that the tube, the tube-to-nozzle glue joint, and joint between the nozzle and jumper tubing are all leak tight. Three tube assemblies were tested. The reported leak rates are 1.6, 3.35, and 2.9 x 10-5 STD-C/sec.

---

[6] \\Ppdserver\MD.PPD\Projects\SiDet\Engineering_Notes\PEEK_Testing\SIST Final Paper - 2a.pdf

[7] \\Ppdserver\MD.PPD\Projects\SiDet\Engineering_Notes\PEEK_Testing\Adhesive Test Results Eng Note.pdf

[8] The second tube produced was assembled into the stave core used in the adhesion test described above.

Bubble clearing and leak rate considerations

H. Jostlein has investigated[9] the ability of the tubing to clear bubbles under operating conditions. Solutions of 0%, 40%, 80% and 100% glycol in water were tested at room temperature to simulate extremes of viscosity and surface tension. The tubes were tested in their nominal orientation as well as “reasonable attitudes and rotations”. Bubbles were observed to clear well at flow rates of 60cc/min or lower, roughly 1/3 of the expected flow rate in the tubes. Hans summarizes:
“A leak in a sub-atmospheric system can generate gas bubbles. Bubbles appear to be sub-atmospheric system can generate gas bubbles. Bubbles appear to be carried away rapidly and completely by the coolant flow at flow rates well below the expected operating conditions. Coolant flow is not impeded.”

If we assume that the Ne leak rates we are currently observing are representative of the rate at which air will enter the system then we can estimate the total air volume that the air separator would need to remove per day. With a leak rate of 3 x 10-5 STD-CC/sec and 168 tubes in the system we would see a total of 435 CC/day of air in the system. This is well below the capacity of the air separator and should have no impact on the cooling system performance.

Irradiation tests

A set of 6 samples of PEEK tube were irradiated to 18 Mrad at the booster. Samples were round tubing. A set of 6 control samples, not irradiated, were also tested. Tubes were pressurized to failure. Failure pressures for irradiated samples were 525-570psi and for control samples 520-625psi. Tube failures were not in the irradiated region in 5 of 6 samples (both the irradiated and control samples had 5/6 failures at the end connections). Dan Olis performed these tests[10].

Burst tests

In addition to the burst tests done as a part of the irradiation study, free-standing formed tubes were also pressurized to failure. For this test we used very early samples of 6” long U-tube roughly 2mm x 6mm cross-section and preferentially selected very poor looking samples. The samples burst at 95 and 97 psi. The purpose of this test was to verify that we could safely pressurize tubes to 25 psi for a bleed-down leak test. These tests were performed by Ken Schultz.

Stave core pressure and vacuum tests

A bare stave core, without outriggers and pin holders, was pressurized to 25 psi internal pressure to evaluate deflection vs. pressure and potential delamination. There was no indication of glue joint failure. The tube displacement at mid-span was linear with a magnitude of 0.002”/psi. Another core assembly was evacuated to –5 psig and the deflection was of the same magnitude.

---

[9] E-mail dated 10/25/02 (\\Ppdserver\MD.PPD\Projects\SiDet\Engineering_Notes\PEEK_Testing\Hans Email.pdf)
[10] \\Ppdserver\MD.PPD\Projects\SiDet\Engineering_Notes\PEEK_Testing\Irradiation Test Results.pdf

A core populated with only 10/10 stereo and axial modules made from blank silicon was subjected to full vacuum within the cooling tube to test for catastrophic failure of silicon during possible leak testing of the assembled detector and to understand silicon deflections which may result with the coolant system running subatmospheric. With full vacuum in the cooling tube, 10 to 13 microns of local dishing of the silicon above the cooling tube was measured. With – 5 PSI in the cooling tube, the expected operating condition during installation, this scales to about 4 microns of local deflection over the cooling tube. This is well within the silicon flatness requirements.

During commissioning of the detector, leak tests of the cooling system will need to be done. One leak test option requires a vacuum applied to the cooling system, which would include the stave cooling tube. Full vacuum was applied to a mechanical stave assembled for thermal tests to determine if the silicon might develop cracks. The stave is outfitted with dummy silicon and bare BeO hybrids and includes C-channels and channel braces. No catastrophic failure of the silicon occurred after 24 hours at full vacuum.

Long-term flow test

There are 5 PEEK tubes, 2 free-standing and 3 in assembled CDF stave cores, which have been operating in the long-term flow test stand. These have PEEK nozzles glued with 2216 adhesive as we propose for our final tubes, so they are a relevant test of the integrity of the tube to nozzle joints, as well as the parent material. There is no evidence of leaks in any of these tubes, i.e. no visible air bubbles being generated.

Thermal expansion of PEEK

The stress induced in the silicon from thermal expansion is proportional to EA*CTE. The CTE here is really the difference between the tube and the silicon, roughly 31ppm/C for PEEK/Kapton. The silicon is a factor >50 stiffer than the PEEK tubing, so the effect of cool-down is to induce tension in, or stretch, the PEEK to match the cold sensor length. The induced stress in the PEEK and Kapton is about 650psi, well below their elastic limits. The sensor stress is <350psi making the worst-case assumption of infinitely rigid glue.

Moisture expansion measurements of PEEK tubes

PEEK tubes exposed to glycol/water in the long-term flow test were used to measure the moisture expansion of the tubes. Fiducials were located on the tubes roughly 500mm apart on each leg of the tube. The distance between the fiducials was measured with the tube “wet”. Afterwards the tubes were dried by flowing dry air and heating to 150F overnight and re-measured. The PEEK tube elongation was 0.022±0.008% (122 μm). The tubes shrank when dried. The differential thermal expansion values for 30º C temperature change is 0.093% for PEEK. Note that the thermal and moisture effects have opposite signs for PEEK, relative to the silicon.

Liquid nitrogen quench

The test: five (5) formed PEEK cooling tubes were leak checked, dunked in LN2, and leak checked again. Leak test done using neon sensitive leak detector. Tubes are leak checked by inserting into a vacuum chamber and internally pressurized with neon gas to approximately 3" WC. Leak detector pumps on vacuum space around tube. The results are recorded here:

	Leak Rate [std cc/sec] of Neon	
Tube s/n	Before LN2 Quench	After LN2 Quench
24	1.5×10^{-5}	1.5×10^{-5}
25	2.3×10^{-5}	1.6×10^{-5}
26	2.3×10^{-5}	1.9×10^{-5}
27	2.7×10^{-5}	2.2×10^{-5}
28	5.4×10^{-5}	2.3×10^{-5}

Test performed by Ron Davis at PAB.

Tube and core flatness and parallelism considerations

Because the PEEK tube is not stiff it is necessary to apply light positive pressure inside the tube during core fabrication and during module installation to avoid "hour-glassing" of the tube. Currently 5 psi is used during stave core fabrication and 0.8 psi during module installation. The resulting cores have been found to be of uniform thickness to 0.001" generally. This is determined almost entirely by the accuracy of the machining of the core components. The first full core built has been measured for parallelism on the module installation fixture bare core holder. We measure parallelism rather than flatness of the top surface to remove the 0.0015" bow of the fixture. The measured parallelism is 0.002". The PEEK cores show no significant twist or natural curvature that we expect will affect the final sensor positioning in a completed stave assembled using the designed tooling.

Thermal cycling

The first mechanical stave (alumina hybrid dummies) was cycled >50 cycles from –15C to +20C[11]. The cycles were generated by running coolant in the stave with power off, then turning the cooling off and turning heaters simulating the SVX chips on. This is a fairly severe test as it generates large thermal gradients in the silicon, which would be more likely to produce glue joint failure. Temperature profiles were measured during the testing and a comparison made of the data from the start of this testing to the end. There was no measurable change in heat transfer and no visual indication of glue joint failure.

Additional cycles were made from –10C to +20C for >5 cycles. Again there was no indication of any degradation to the stave or modules.

---

[11] \\Ppdserver\MD.PPD\Projects\SiDet\D0_Notes\D0_StaveThermalData\D0 StaveThermalData